

## CHAPTER 6

### WATER CONTROL ANALYSIS TECHNIQUES

#### 6-1. General Considerations

a. Importance of Technical Evaluations. Effective regulation of a major water resource system in real-time ultimately depends upon the experience and judgment of the water control manager. Complex interactions among the many meteorologic and hydrologic processes, combined with the effects of project control, encompass a wide spectrum of continuously changing conditions which must be evaluated and understood. Judgmental decisions made by the water control manager must be founded on the best available scientific and engineering evaluations, considering time constraints and available data. There are many analytical tools now available that may be used to quantify those elements which would otherwise be subjectively determined. Accordingly, it is the overall objective to perform technical evaluations based on rigorously defined analytical procedures, rather than subjectively determined estimates. The technical methods used in analyzing water resource systems are of prime importance in the overall accomplishment of water management objectives. They constitute the technical support by which the water control manager may form decisions during actual project regulation.

#### b. Hydrologic Analysis - Historical Data

(1) One of the primary technical problems in managing water control systems in real-time is hydrologic analysis. Water is the prime resource to be managed in water control systems, and this demands full knowledge of the natural processes by which water is distributed and accounted for in a river system. The science of hydrology is defined as the body of knowledge related to the behavior of water as it occurs in the atmosphere, on the surface of the ground, and underground. Although hydrology is considered to be a science, there is a blending of scientific theory and empirical knowledge in the application of hydrology to the analysis of river systems.

(2) For many years, the Corps of Engineers has utilized widely accepted hydrologic analysis procedures in design flood hydrology. Specific reference is made to Chapter 5 of EM 1110-2-1405 for a discussion of factors to be considered in determining the magnitude of design floods. Application of these principles was extended to rivers affected by snowmelt runoff and is described in EM 1110-2-1406 and Chapter 10 of "Snow Hydrology" 10/. Initially, these methods were used for project planning and design studies, but more recently

they have become the basic method of analysis for project operation and real-time project regulation. During the past 3 decades, detailed methods of analysis have been refined through continued development and application of computerized procedures for analyzing runoff.

(3) Long-term analyses of river and project conditions are based on historical or derived streamflows that are used in connection with the development of water control plans. Simulations of project regulation are computed by system analysis techniques that will portray river and reservoir conditions for an extended period of time, based on current reservoir conditions and historical streamflow data. Thus, this type of simulation may be made to test the system's capability to meet its water demands over a long period of record (30 to 50 years), based on current project conditions, recent operating criteria, and historical streamflow data. Simulations of project regulation may also be made that consider each year of historical record as an individual event. This is useful in obtaining a probability distribution of project regulation conditions during the ensuing year or a portion thereof, in order to assess the probabilities of meeting water demands based on historical records of streamflows, current reservoir levels, and water or power demands.

(4) In summary, the overall objective in analyzing water control systems in real-time is to use all the current water control data available to apply the analytical procedures necessary to regulate projects in the most effective manner possible. This will provide information to schedule the regulation of individual projects and to obtain outlooks of future system regulation. Project regulation schedules must be generalized since they are based on historical data and hindsight operation. When plans are applied in real-time, however, operational decisions need to be made under the guidelines of the water control plan, but adjusted as necessary to meet any unique conditions.

## 6-2. Computer Utilization for Water Management

### a. Basic Principles

(1) Computers are now an accepted means for problem solving generally throughout the Corps of Engineers. Computers are used to solve engineering problems encountered in planning, design, and construction of water control systems, and this is especially true in the fields of hydrology, hydraulics, and water management. Computers were first applied to water management problems in the mid-1950's, in connection with application to hydrologic simulation and reservoir system analysis. The expansion of techniques has continued since

that time, paralleling the expanding technology of data processing systems. Now a major array of hardware and software systems are fully developed and available for general use. Furthermore, engineers are now trained to utilize these systems, and they are accustomed to solving the data handling and analytical problems that these systems present.

(2) Initially, these computerized hydrologic and system analysis techniques were applied to planning and design functions, but there were also major efforts to develop the techniques for real-time project regulation. As a result, there has been a steady refinement of the programs and models that can be applied to water management activities, and this will continue into the future as the technology and data systems improve.

#### b. Concepts in Computer Utilization

(1) In hydrologic simulation and reservoir system analysis, the computer provides a means for data processing and problem solving that would otherwise be completely infeasible. The continuous simulation of water resource systems for a major river basin requires large amounts of data and computational power, as well as data processing systems that are convenient to the user, in order to apply the procedures to real-time water management. Therefore, the design of these systems must be oriented with this basic concept in mind. One of the major design factors for real-time analysis is to provide a system that can be used with a minimum time required for input data preparation, data handling, and interpretation of output. Furthermore, the algorithms that express the hydrologic functions affecting streamflow must be based on sound hydrologic theory, but they must also be practical representations of hydrologic processes considering the availability of basic data, quality of the data, and data processing requirements.

(2) These programs constitute tools that can be used by the water control manager to enhance technical knowledge of water conditions within the system. Improved water control decisions and detailed schedules can be made as a result. In summary, computer evaluations should be considered only as an analytical tool by which the water control manager may conveniently test various alternatives and conditions affecting regulation within the framework of the water control plans.

#### c. Types of Models

(1) The types of models which may be applied to real-time project regulation may be generalized into the following groups:

(a) computer models used to simulate hydrologic processes and thereby synthesize streamflow, in order to forecast flow resulting from rainfall or snowmelt estimated from known hydrologic conditions and forecasts of future meteorological events;

(b) reservoir system analysis models used to simulate single or multipurpose projects, based on observed or derived streamflows, in order to determine future project capabilities from known river and reservoir conditions;

(c) reservoir water temperature and water quality models used to simulate the conditions of water quality in a reservoir and at downstream locations for assessing future conditions of water quality and scheduling the operation of multilevel outlet works or other facilities related to water quality control at the projects;

(d) water supply and forecast models used to forecast seasonal runoff, based on statistically derived procedures using indexes of hydrometeorological variables;

(e) special auxiliary programs used to determine water release schedules, summarize data, display data, and analyze particular functional needs that affect water regulation.

(2) A brief description of commonly used computer programs that perform many of the described functions is included in Appendix C, EM 1110-2-1701. References 11 through 16 give detailed descriptions of several application programs.

### 6-3. Meteorological Forecasts Used in Water Control Management

#### a. General

(1) River system response is ultimately the result of hydrometeorological factors that affect runoff. The time, form, and areal distribution of precipitation, together with meteorological factors that affect energy inputs that cause evapotranspiration and snowmelt, are controlled by meteorological processes in an ever-changing atmosphere. The analyses in the preceding sections are concerned not only with the current conditions of hydrometeorological factors affecting runoff, but also with projections of these conditions into the future. For this reason, meteorological analyses are an important consideration in making forecasts and projections of project regulation, and the water control manager should have basic knowledge of weather-related phenomena, both physical and statistical.

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(2) All streamflow forecasts must make some specific assumption regarding additional meteorological input during the forecast period. These expectations may be based on subjective evaluations made from cursory examinations of current weather data, or by detailed analyses and forecasts that quantify the expected precipitation, air temperature, wind, humidity, solar radiation, and other factors that affect the hydrologic balance during the forecast period. Basic weather forecasts are prepared nationally by the National Weather Service (NWS). The basic weather data and national analyses are available to Corps offices through direct computer connections, telecommunication systems, and charts and maps. Local or regional analysis may be done by the local offices of the Corps or through cooperative arrangements with the NWS forecast offices.

(3) Analyses may be performed to provide a family of forecasts covering a range of future meteorological conditions. Application of weather data beyond the time range of reasonably accurate weather forecasts requires additional special weather analyses for use in water management activities. Assumptions must be made for input to computerized streamflow simulations for medium- or long-range projections of streamflow or weather related variables that will best represent the most likely occurrences of these elements. Such assumptions may be based on single valued climatological averages or multivalued statistical arrays, which can be used to represent the statistical variability of future runoff events. These analyses may be used to determine not only most likely projections of future runoff and project conditions, but also extremes that may occur under unusual circumstances. This type of analysis is of particular importance to the water control manager who needs to know the potential for controlling future flood events that may occur, or for assessing the potential for low-flow or drought conditions, based on current hydrometeorological and project conditions.

#### b. Short-Term Weather Forecasts

(1) Quantitative Precipitation Forecasts (QPF). One of the more important types of weather forecasts for project regulation is the Quantitative Precipitation Forecast (QPF). Normally, weather forecasts are performed by the NWS, either in conjunction with their National Weather Forecast Center or through state Weather Service Forecast Offices. The NWS Quantitative Precipitation Branch in Washington, DC, prepares a daily national map showing isohyetal lines of 24-hour QPF for the country as a whole. This information is transmitted on the NWS Automation of Field Operations and Services (AFOS) network and is available to Corps offices as a program licensed by the NWS. The AFOS system replaces the facsimile system previously used. The national QPF map is generalized and does not

provide detailed information required for individual projects or river systems. More detailed analyses and forecasts may be made at the local or regional level. This may be accomplished through cooperative programs with the NWS State Forecast Offices or River Forecast Centers or by meteorological specialists within the Corps. QPF's may be developed as 6-hour values for specified locations or drainage basins, for 2 days in advance, and for a 24-hour value for the third day.

(2) Air Temperature Forecasts. Air temperature is important to hydrologic forecasting for differentiating the form of precipitation as rain or snow, and as an index to snowmelt rates, where snow is a significant contribution to runoff. The weather analyses required for QPF may also be used for determining forecasts of air temperature. The forecasts are usually specified as maximum daily, minimum daily or period-by-period air temperature values for index stations. Closely allied to forecasts of surface air temperatures are forecasts of upper air conditions at particular atmospheric levels, freezing levels, or melting levels. Forecasts of this type are particularly important for determining the areas of rainfall and snow accumulation in mountainous regions.

(3) Forecasts of Snowmelt Runoff Parameters

(a) Hydrologic forecasts for those rivers that are fed at least in part by snowmelt runoff need weather forecasts of appropriate snowmelt parameters. Evaluations of snowmelt runoff are very complex from a theoretical point of view, and considerable research effort has been made to determine the relationships between meteorological parameters and snowmelt runoff (see Reference 10 and EM 1110-2-1406).

(b) Weather forecasts required for snowmelt runoff forecasting are generally confined to forecasts of air temperature. Forecast air temperature are used as indexes for snowmelt. The air temperature forecasts may be either maximum temperature, mean temperature, or a combination of maximum and minimum temperatures. Under some circumstances other parameters may be included in determining snowmelt indexes, such as dew point, relative humidity, wind, or solar radiation 10/, but these are not generally used in operational forecasting.

(4) Weather Forecasts for Tidal Barrier Regulations

(a) Hurricanes. Engineering Manual 1110-2-1412 provides guidance for storm surge analysis and design water level determinations in coastal areas. The factors affecting operations for a hurricane are its forward speed as it moves toward a project and the track of the storm center as it approaches the coastline.

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Speed of the storm, which often accelerates as it moves into the northern latitudes, affects the time permitted for mobilization, closure of gates and general preparation for the tidal surge. Location of the storm track relative to a coastal community influences the magnitude of the surge. All hurricanes and other cyclones in the northern hemisphere rotate in a counterclockwise direction. Winds are highest in the right side of these storms, and storm surges will be highest in this side since winds will be blowing on shore. Therefore, when the storm center passes to the left of a project, the project will be susceptible to the worst effects of the hurricane. The components affecting storm surge consist of the forward speed of the storm, hurricane wind speed, and low barometric pressure. All of these components are additive. Such conditions may cause abnormally high tides and waves that are often intensified at the head of coves and bays. It is not yet possible for the National Weather Service to predict with a high degree of reliability whether the track of a hurricane, possibly several hundred miles away, will pass to either side of a community. Thus, in operating a hurricane project, it is necessary to assume that mobilization of personnel and closure of gates will be required. It is anticipated that some of the storms, for which preparations have been completed, will veer away and produce no appreciable tidal surge.

(b) Extratropical Storms. Extratropical storms also produce abnormal tides above damage stages; for these storms, operation of a barrier is dependent upon the wind speed and direction as well as the predicted tide and estimated surge. From past studies and operating experience, it is evident that highest abnormal tides during an extratropical storm nearly coincide with the time for a predicted astronomic high tide (within 1 to 2 hours). Therefore, the time of operational requirements can be more readily predicted than for a hurricane. However, slow moving extratropical storms often produce abnormally high levels for several consecutive tide cycles, which may require more than one operation of a barrier.

(5) Severe Weather Forecasting. Beyond the activities involved in management of water control systems, the Corps of Engineers needs real-time weather forecasts in connection with the operation of its floating plant and field installations. Forecasts of anticipated severe weather (primarily wind and storms, but including other unusual weather conditions) are required to meet not only the needs in connection with operation of water control projects, but also for the safe operation of all land based and floating equipment. Inasmuch as liaison between the National Weather Service and the Corps of Engineers is maintained through those elements of the Corps dealing with water management activities, weather forecasts for general use within Corps activities are supplied through the appropriate water management, reservoir control, or water regulation

units within the Division or District offices.

c. Long-Range Weather Forecasts. Long-range (monthly, seasonal, or annual) weather forecasts are considered to be experimental. Their accuracy, when compared to the use of statistically derived climatological averages, does not warrant their application to management of water control systems. The water manager should be cautioned not to place a "partial" trust in long-range weather forecasts for "shading" project regulation criteria in response to such projections. An unjustified use of such forecasts may, in the long run, result in misregulation of project facilities and under extreme conditions, jeopardize the authorized functional use of the projects. Monthly weather outlooks do show some relatively modest degree of forecasting skill in comparison with using climatological averages of historical data.

#### 6-4. Simplified Manual Methods for Analyzing River Response

a. Backup Procedures. Manual analytical procedures may be required to assure continuity of project regulation. Simplified analytical techniques should be available for use by field or project offices in the event that communication is lost between the control center and the projects. For these reasons, generalized manually applied aids should be developed which can be used in an emergency. These would be simplified index procedures or graphical relationships that can be used to estimate runoff conditions from whatever data may be available. They may also be guides for project regulation as determined from known project inflows or other water control data. These aids or guides may be developed from analyses of historical data, and they may also be derived through use of the computerized methods for simulating hydrologic conditions and project response.

b. Graphical Runoff Relationships. A particularly convenient and useful method for deriving multivariable graphical aids for estimating runoff is based on the use of calibrated hydrologic simulation models. As a study program, the forecasting diagrams are derived by simulating the runoff processes for a range of conditions, including variable amounts of rainfall and variable initial conditions of the basic soil moisture and base flow infiltration indexes. This information can be generalized into linear or curvilinear relationships as multiple-function co-axial diagrams. Forecasting diagrams of this general type have been developed for use in operational forecasting (see Linsley, Kohler, and Paulhus, "Hydrology for Engineers" 17/), based on observed conditions of rainfall and runoff that have been correlated with computed runoff index values, as, for example, the Antecedent Precipitation Index API method. The use of a computer simulation model in developing these

relationships has a particular advantage over the use of observed data since the various ranges of values for each of the runoff indexes and rainfall amounts may be tested as individual parameters. Thus, a series of simulation runs covering all ranges provide an array of data which can conveniently be put into a graphical relationship, whereas the use of historical data is limited by the ranges and amounts covered in a relatively small sample of hydrologic events. Further, a procedure that is based on runoff characteristics derived from multiyear calibration studies for streamflow simulation models provides better evaluations of runoff potentials than less rigorously determined correlation techniques.

#### 6-5. Long-Range Predictions of Streamflow

##### a. General

(1) Up to this point the discussions of streamflow analysis and related weather forecasts have dealt with short-term outlooks covering a few days, or extended to a few weeks as medium-range projections. There is a need, however, to consider long-range predictions of streamflow which cover periods of several months in advance of the date of forecast. As indicated in Paragraph 6-4c, long-range weather forecasts can be considered at this time only as experimental and not of sufficient accuracy for application to real-time project regulation. The interrelationship of hydrometeorological factors affecting runoff imposes similar restrictions in long-range streamflow forecasts, but there are some hydrologic factors having carry-over effects which provide the ability to develop useful and reliable long-range streamflow forecasts. Situations for which long-range streamflow forecasts may be significant are described in the following paragraphs.

(2) For rainfed rivers, these effects are limited to long-term changes in ground water conditions that may be determined at a particular time and projected into the future as a basis for long-range streamflow forecasts. The accuracy of such forecasts limits their use to assessing general trends in low-flow conditions of runoff that may have significant effects on project regulation for hydropower or water supply functions. These long-range streamflow forecasts for rainfed rivers would have little or no significance to flood regulation.

(3) The runoff from predominately mountain snowfed rivers, on the other hand, may be forecast several months in advance on the basis of known conditions of the accumulation of the snowpack over the watershed. In general, the snowpack accumulates progressively through the winter season and then melts in the late spring or early

summer. The knowledge of the water equivalent of the snowpack provides as much as 4 to 6 months advance notice of the expected runoff volume. Forecasts based on this knowledge are extremely useful in managing project regulation for all purposes, including water supply, irrigation, navigation, flood control, hydroelectric power, fish passage, recreation, and other environmental functions. Long-range forecasts of snowmelt runoff provide a direct measure of the volume of runoff to be expected in the runoff period, but they do not forecast the time-distribution of runoff. Factors affecting daily snowmelt are related to weather parameters that cannot be forecast on a long-range basis.

b. Statistical Procedures for Forecasting Seasonal Snowmelt Runoff Volume

(1) There is a long history in the development and application of procedures used for forecasting seasonal snowmelt runoff volume. This development has occurred mostly for the rivers of the mountainous West, in connection with regulation of multipurpose projects, and for management and forecasting of uncontrolled rivers as related to irrigation developments and flood control needs. Some of the principles involved in these methods have also been applied to rivers in the Northeast, Middle West, and Alaska. Nearly all of the procedures are based on the use of relatively simple month-to-month indexes of snow accumulation and precipitation. Refinements in procedures are made through use of indexes of other factors involved in the water balances of the areas, including soil moisture increase, evapotranspiration, and changes in ground water storage. The forecasting relationships are derived either by graphical analysis or by mathematical statistical correlations of runoff with single or multivariable indexes. This type of analysis generally utilizes the multiple linear regression technique, applied to historical data of runoff and index parameters. Some procedures transform the variables logarithmically or exponentially, whereby the correlations become curvilinear rather than linear. Although nearly all procedures are based on statistical analysis of simplified indexes of runoff, some attempt has been made at a more rigorous water balance approach to seasonal runoff forecasting.

(2) Chapter 11 of "Snow Hydrology" <sup>10/</sup> presents a summary of methods used in developing procedures for forecasting seasonal snowmelt runoff volume. It describes the index and water balance approaches and discusses at length the various indexes that may be used. In summary, the main emphasis of procedural development is to use rationally based indexes that represent the water balance of the area involved. The primary index is normally that of snow accumulation, which may be represented by direct measurement of snow accumulation at snow courses or by indirect measurements of seasonal

precipitation at selected climatological stations.

c. Use of Deterministic Hydrologic Models for Long-Term Streamflow Forecasts

(1) A logical extension of the use of deterministic hydrologic models is their application to long-term streamflow forecasting, as an alternative to the use of statistically derived forecasting procedures. The principle objective in formulating statistical procedures for forecasting seasonal snowmelt runoff volume is to select indexes which are most highly correlated with runoff and are also representative of the physical hydrologic processes defined by the water balance of the area involved. Although the lumped hydrological parameters used in deterministic simulation models are also considered to be indexes of the hydrologic processes, they represent an average basin or zonal value of these processes, as best estimated from a large array of available data. The model simulation is considered to represent the water balance of the area involved. The models are rigorously applied in daily or smaller time increments to best represent the physical processes of snow accumulation, snowmelt runoff, and all other hydrologic processes involved in the water balance of the area.

(2) Deterministic hydrologic models not only can incorporate all of the data used in statistical procedures, but also can utilize additional data that pertain to evaluations of snow accumulation and other hydrologic processes, and thereby better represent the true determination of those factors that affect future runoff. Therefore, deterministic models account for the processes in daily or smaller time increments and provide a much more rigorous analysis of runoff events than can be done by monthly based statistical methods. Further, the fact that the application of this type of model allows for maintaining daily continuity of all hydrologic parameters in a forecast mode permits a continuous appraisal of runoff conditions for operational forecasting in a way that is completely infeasible with statistical models developed from monthly data. This is particularly important for appraising changed conditions of runoff potential at any time within the month-to-month forecast evaluation period commonly used with statistical procedures. These procedures also allow for rational determination of the effects of an array of assumed weather conditions subsequent to the date of the forecast; examples are median, mean, percentile of exceedence, or extremes. For these reasons, there will be a gradual transition from the use of statistically based procedures for forecasting seasonal snowmelt runoff to procedures based on the use of deterministic hydrologic models.

## 6-6. Long-Range Analysis of Project Regulation

### a. General

(1) Long-range analysis of project regulation may be necessary on a current real-time basis in order to assess the planned regulation, beginning with currently known project conditions and with knowledge of current regulating criteria, which may include revisions to the generalized criteria contained in the water control plans. Projections of this type are used primarily in connection with analyzing project regulation requirements for hydropower, water supply, or environmental considerations. Examples of revisions to water control criteria would be changed hydropower requirements caused by revised load estimates or unplanned plant outages, special requirements for preserving fish runs, or other functional or environmental needs that arise on a current basis that were not anticipated in the water control studies.

(2) As discussed in Chapter 3, development of the water control plan involves a lengthy process of studying project regulation from the planning and design stages to preparation of the regulation schedules and their documentation in the water control plan. Further, an annual operating plan may be developed that applies the regulation principles contained in the water control plan to the current year's regulation. The regulation would be based on assumed hydrologic and project conditions, which may depart significantly from actual conditions. Accordingly, there is a need to re-evaluate the current regulation as conditions change from those contained in the water control studies, in order to reflect the effects of the current operating experience on future regulation.

b. Analytical Techniques. The methods used for this type of analysis are essentially the same as those used in developing the water control plans, but there may be some modification in the methods of application of those techniques. Thus, the concept of computerized reservoir system analysis, which is fundamental to planning system regulation, can also be applied to current regulation of a system of multipurpose projects. The analyses used to develop water control plans and simulation models that can be used are discussed in Chapter 3.

c. Basic Data and Types of Analyses. Long-range analyses normally cover the current year's operation, but in situations where there is planned use of reservoir storage over a multiyear critical period, the projections may be extended over a 2- to 3-year period. The hydrologic data used as input for current system analysis studies are the same historical mean monthly streamflow data used in water control studies, but there may be a minor modification of streamflow

data to reflect a transition from the currently observed streamflow conditions to the historical data. The historical streamflows can be analyzed to represent the effect of the most critical streamflow sequence on system regulation, a statistically derived sequence of streamflows representing median or mean conditions, or an analysis of the entire historical record as a continuous process to determine the long-range effects of future system regulation based on the most recent data. Also, it may be desired to test the current year's regulation by analyzing system regulation for each individual year's historical streamflow data as an independent event, commencing with the current project conditions, and thereby obtain a statistical distribution of future probabilities of all of the elements of system regulation for the remainder of the operating year.

d. Utilizing Results of Long-Range Analysis

(1) The long-range analyses of system regulation as discussed above have their greatest significance in assessing low-flow water supply and hydropower capabilities. Specifically, they provide the technical evaluations necessary for optimizing power production, for determining the strategy for marketing surplus power, for assessing probabilities of meeting firm power commitments, and for determining the probable effects of power operation on nonpower functions. The same principles of analysis may also be applied to assess future conditions of regulation as related to other project functions, such as irrigation, water supply, recreation, fish and wildlife, and other environmental uses. Thus, by maintaining continuity and surveillance of system regulation, long-range analyses provide the water manager with the ability to anticipate future conditions that may be adverse to meeting the overall water management goals and to take appropriate corrective action in time to be effective.

(2) In summary, real-time long-range projections based on monthly reservoir system analysis techniques are used primarily as an aid in regulating large multipurpose reservoir systems. The importance of such analysis depends on the particular hydrologic and project conditions that are being experienced. Under near normal streamflow conditions, with no significant changes in the operating criteria from those contained in the operating plan, and with no special problems related to system regulation, there may be little need for this type of analysis. On the other hand, unusual circumstances often occur that require careful study to determine the future consequences of project regulation. Any modification of the planned regulation to meet such circumstances does indeed depend upon these types of long-range projections, and reanalysis on a monthly or weekly basis may be required.

## 6-7. Water Quality Forecasting

a. General. Up to this point this chapter has dealt with water management techniques that are geared basically to managing the quantity or potential quantity of water in a river-reservoir system. There are many environmental impacts that are attributed to Corps water control projects, and some are quite significant. It is essential that the water control management team recognize and address to the fullest the environmental potential of each project or system of projects they manage. This awareness comes from a team approach, blending and balancing a wide range of disciplines which should include hydraulic engineers, water chemists, biologists, and whatever other specialty the particular system warrants. These team members must be part of the real-time operation of the projects. It may not be sufficient to leave the day-to-day decision making to the hydraulic engineer alone since this process often offers the best opportunity to generate environmental benefits from water control projects. Many situations and opportunities arise in real-time water control management that can only be recognized by specialized team members. Several important aspects of water quality management of Corps projects are forecasting future quality, evaluating existing quality, and predicting the effect of various management options on the projects and the areas influenced by the projects. There are several analysis and forecasting techniques available.

b. Analytical Techniques. Analytical techniques used vary widely but follow the same general types of analysis that are involved in weather, flow, and volume forecasting. These analyses may involve computer simulation of historical records to evaluate various management options for planning purposes or be models of real-time, existing conditions that allow tests of a variety of management choices on present and future water quality conditions.

### c. Forecasts

(1) General. There are many aspects of water quality that may need forecasting. Some of the more typical parameters are temperature, dissolved oxygen, turbidity, nutrients, sediment, pH, dissolved solids, algae, fish migration, metals, and contaminants. It may be necessary to establish long-term cycles of some parameters such as temperature to evaluate the impact of various operating scenarios on the project waters and on the downstream zone of influence. In other cases it may be important to forecast short-term factors, such as the passage of an "acid slug" in a stream influenced by mine drainage, and develop real-time response to deal with it. Water quality forecasting is usually the sole responsibility of the water control manager, and he must decide what to forecast, how to forecast it, and how to use the forecast in his decision process.

Some reservoirs have long memories, and management decisions made today may have an impact that will last for years. It must be understood that long after the physical and chemical effects of a management decision are gone, the biological consequences may linger for weeks, months, or years depending on the project and conditions around it.

(2) Long-Range Forecasts. Long-range forecasting of water quality should include projection of conditions as far in the future as is practical and useful to project management decision making. Reasonable forecast computer models for many physical and chemical parameters can be used to estimate weeks and months ahead. Long-range forecasting can also be much less sophisticated, utilizing a graphical evaluation and projection of conditions. EM 1110-2-1201 is a good reference for analytical techniques. Long-range forecasting is usually important to large projects with longer retention times.

(3) Near-Term Forecasts. Near-term forecasts are those that evaluate or forecast for only a few days or, at most, a week or two. These forecasts are used to evaluate real-time conditions and project management alternatives that do not have far reaching consequences and may be especially useful for managing small projects. Near-term water quality forecasts should always be made to evaluate the consequences of possible project management alternatives prior to making a decision. These decisions may be as simple as changing a port in a selective withdrawal tower or decreasing a release to stabilize a pool level. Each decision in one form or another is based on a forecast. Decisions should not be based solely on a flow forecast but also include a quality forecast to determine if there are better alternatives and how it may be possible to control the environment of the project in a more positive manner.

## 6-8. Special Hydrologic Analyses

### a. General

(1) There are many other special types of analyses that deal with specific hydrologic problems, including:

- determination of streamflows and water level in a major river which incorporates diversion structures in the control of water levels (e.g., the Lower Mississippi River), where the determination of unsteady flow conditions within the confines of the river itself is the dominant hydrologic problem
- behavior of rivers and reservoirs under conditions of ice and

sedimentation, and their effects on projects, project operation, channel capacities, and flooding along the rivers

- effects of winds, storms and tides on water levels in rivers, lakes, and estuaries, together with their effect on determination of project inflows
- determination of reservoir evaporation and its effect upon regulation
- determination of effect of bank storage on reservoir capacity
- changing effects of forest removal and urban development on runoff

(2) The above list indicates only the more general types of hydrologic problems that are encountered during water management activities, and each river system has its own set of problems which may involve many other facets of hydrologic analysis. The particular analytical methods for solving these problems are usually developed by the operating office in which they occur, and their use is usually limited to their particular areas of application. The following paragraphs summarize briefly some of the specific problems and methods that have been developed for solving these problems.

b. Unsteady Flow Determinations in Major Rivers. There are many methods commonly used for simulating the response of river systems subjected to unsteady flows. Streamflow routing procedures range from simple, empirical methods for translating and computing the attenuation of the unsteady flow fluctuations, to highly complex and completely rigorous computerized solutions of the unsteady-state flow equations. Each has its use for particular types of applications, depending on the type of river system, the general ranges of flow variations normally experienced, the effects of variable backwater conditions caused by tides, project operation, or "looped" ratings of channel flow, the overall accuracy of the computed fluctuations in relation to the needs for a particular application, the time and effort that can be expended in the solution for timely use, and the availability of basic data required for application.

c. Effects of Sedimentation in Rivers and Reservoirs. Sedimentation has long been an important aspect of planning and designing projects. In the operational phase of water resource development, recognition must be made of the potential problems that may develop as the result of sediment deposits in both reservoirs and natural stream channels. The problems may involve the loss of active storage space in reservoirs, changes in channel characteristics and

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sedimentation balance for rivers downstream from projects, effects of sediment deposits in small tributaries entering reservoirs, changes in maintenance dredging resulting from water control, and the lack of knowledge of sediment density currents in reservoirs. These effects relate to water management activities in relation to changing conditions for downstream control, managing water levels, and controlling the regulation of multilevel intake structures or other outlet facilities.

d. Effects of Ice in Rivers and Reservoirs

(1) The occurrence of ice has major significance to management of water control projects in the northern tier of states and Alaska. River ice forms in the fall or early winter and may gradually increase in thickness until the spring thaw. River ice may constitute a major threat for flooding as the result of ice jams that build up at critical locations, especially at the time of the spring thaw or at other times when streamflows increase and the ice jams severely restrict the flow of water in the river channels. The prediction of the occurrence of ice jam flooding is particularly important where it may involve the release of water from upstream reservoirs. Ice jams are also likely to occur where tributaries enter reservoirs. This is mainly the result of reduced channel velocities in the river immediately upstream from the reservoir. This type of occurrence may require special regulation of the water surface in reservoirs to help mitigate adverse effects in the upstream tributaries. The occurrence of ice in river channels also affects the flow rating relationships used for determining streamflows from reports of water levels, and special efforts must be made to properly apply rating curves under these conditions. Formation of ice in reservoirs is common in cold climates, and ice cover may persist for as much as six months, with thicknesses up to three feet. The occurrence of ice on large reservoirs is of concern in the vicinity of the dam or control works, or as it may affect navigation. Ice flows caused by wind may build up in reservoirs in the vicinity of the dam and could impair the operation of outlets, spillways, navigation locks, or other facilities. In cold weather, spillway gates are susceptible to freezing, which may restrict their normal operation, unless specific measures such as seal heaters are incorporated into the design. The occurrence of frazzle ice in penstocks may also restrict the operation of hydropower facilities at certain times.

(2) The U.S. Army Cold Regions Research and Engineering Laboratories (CRREL) have made extensive investigations of the formation and movement of ice in river channels, lakes, navigation locks, and other water control facilities. The results of their investigations are contained in research documents and reports, which

are available from their headquarters office located in Hanover, New Hampshire.

e. Reservoir Evaporation. The hydrologic methods used in river system analysis for managing water control systems usually entail the logical accounting of the water balance from both natural and man caused effects. Reservoir evaporation may result in significant water losses to the river system. These losses are in addition to those which occur by natural evapotranspiration from the drainage area contributing to runoff. The streamflow data used for operational studies are usually adjusted to account for water loss by reservoir evaporation. There are numerous procedures being used for making such adjustments. The degree of refinement in developing these procedures depends upon: (a) the relative importance of reservoir evaporation in the overall water balance of the region and its effect on the management of the system; (b) the types of basic data available to make estimates to be applied to current and historical data ; and (c) practical considerations concerning the accuracy of the estimates to be attained, as compared with the effort required to obtain the basic data and apply it in a computational method.

f. Determination of Effect of Bank Storage on Reservoir Capacity. Reservoir area-storage-capacity curves used in operational hydrology are normally determined by the use of topographic maps of the reservoir area or special field surveys. The reservoir level pool area is determined incrementally for each of a range of elevations that will represent the variations of area and storage within the operating range of the reservoir. These determinations, however, do not normally take into account any possible effects of storage of water within the aquifers underlying the reservoirs. There may be evidence of significant bank storage in some reservoirs, based on the geology of the area and water balance computations. It is believed, however, that in most cases bank storage is not of sufficient magnitude relative to the computed inflow and outflow to warrant its consideration in water control management.

g. Effect of Wind Setup on Water Levels in Reservoirs, Lakes, and Tidal Estuaries

(1) Water levels observed and reported for reservoirs, lakes, and tidal estuaries may reflect the effects of wind or storm tides, superimposed on the hydraulic effects of flow and tides that occur without wind effects. Particularly in lakes and large reservoirs, the normally assumed "flat pool" or "static pool" as used for computation of daily or period inflows from observed outflows and change in storage may be invalid. Inflows computed in this manner may show apparent fluctuations that are not real and reflect the

effects of daily variations in wind on the lake or reservoir. Corrections must be made to properly account for the effects of wind in this type of computation. A practical expedient for doing this is to maintain a continuous graphical plotting of inflows computed from change in storage computations for the reservoir, along with a plotting of key index inflow gaging stations whose streamflows contribute to the reservoir inflow. The total computed inflow is "smoothed" by eye, as judged by the inflow gaging station plots, to best represent the actual variations of project inflows. When the operation of spillway gates or other outlet facilities are determined, the project releases should be based on best estimates of inflow as adjusted for the effects of wind discussed above, or on inflows computed directly from fixed relationships between total project inflow and observed inflows at key upstream gaging stations.

(2) Prediction of the effect of storm tides and hurricanes on water levels in estuaries is of great importance to water management activities in coastal regions. A third factor is the effect of tsunami ocean waves generated by earthquakes that may occur in coastal areas or in the ocean hundreds or even thousands of miles away. Flood protection works that are constructed for protection of coastal rivers and estuaries are designed for the effects of storm tides, hurricanes, or tsunami waves as applicable. When these projects become operational, the occurrence of storms that would affect the areas should be monitored, and, if necessary, special precautions should be taken to insure their proper operation or to institute flood fights. The methods of monitoring and predicting floods under these conditions should be developed on the basis of requirements for particular areas.



Figure 6-1. Table Rock Dam, White River, Missouri;  
Little Rock District